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RESEARCH MEMORANDUM

EFFECT OF SEVERAL DESIGN VARIABLES ON INTERNAL PERFORMANCE OF CONVERGENT-PLUG EXHAUST NOZZLES

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NATIONAL ADVISORY COMMITTEE
FOR AERONAUTICS

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EFFECT OF SEVERAL DESIGN VARIABLES ON INTERNAL PERFORMANCE OF CONVERGENT-PLUG EXHAUST NOZZLES

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SUMMARY

The internal performance characteristics of convergent-plug nozzles are presented for a wide range of pressure ratios. The principles of geometric design for obtaining good internal performance are deduced from these data.

The convergent-plug nozzle has peak thrust coefficients as high as those obtainable with a convergent-divergent nozzle at the design pressure ratio. At pressure ratios below design, the thrust coefficient of the plug nozzle is relatively insensitive to pressure ratio, while that of the convergent-divergent nozzle decreases rapidly because of overexpansion losses.

Contoured plug nozzles designed by the method of characteristics to give parallel exit flow have peak thrust coefficients of approximately 98 percent, which are about 1 percentage point higher than those of conical plug nozzles. The plug angle (simple conical plugs) for the best performance increases with the design pressure ratio. Outer-shell lip angles from 15° to 90° (referenced to nozzle axis) and Mach numbers as high as 1.0 at the plug hump have no effect on the performance of the conical plug nozzle. High Mach numbers at the hump of the plug (0.70) reduce the performance of the contoured plug nozzle by a small amount.

For the same design pressure ratio, a conical plug nozzle is about 10 percent larger in cross-sectional area than a convergent-divergent nozzle. This value is obtained by comparing the ratio of the maximum cross-sectional area to the throat area of a plug nozzle with the isentropic expansion ratio of the convergent-divergent nozzle.

Comparison of two methods of throat-area variation shows that, for a given nozzle size, an iris-type outer shell provides higher thrust coefficients over a range of throat areas than a translatable-type outer shell.

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INTRODUCTION

The operation of many current airplanes and missiles in the supersonic region requires engine components that are specifically designed for high-speed flight. It is desirable in the case of the exhaust nozzle to obtain high efficiencies not only at the design condition but also over a wide range of nozzle pressure ratios. In addition, the exhaust nozzle for a turbojet engine should have a variable throat to compensate for large changes in engine operating conditions. 3843

One type of nozzle that satisfies the requirements for supersonic flight is the convergent-plug nozzle reported in references 1 to 3. It combines the advantage of high thrust coefficients over a wide range of pressure ratios with ease of throat-area variation.

This report summarizes the design data included in references 1 to 3 and a small amount of new data on the convergent-plug nozzle in order to provide the information necessary for good internal design. The plug nozzles were investigated over a range of nozzle pressure ratios from 1.5 to 32. Contoured-plug nozzles designed to expand the flow axially at pressure ratios of 9.3 and 14, and conical-plug nozzles designed for pressure ratios of 8 to 20 were investigated. The conical-plug angle was varied from 40° to 80°. The maximum plug diameter and the plug length upstream of the throat were also varied. Mach numbers at the hump of the plug from 0.25 to 1.00 and outer-shell lip angles from 15° to 90° were studied. Two methods of varying the nozzle-throat area, an iris outer shell and translatable outer shell (or plug), are compared.

APPARATUS AND INSTRUMENTATION

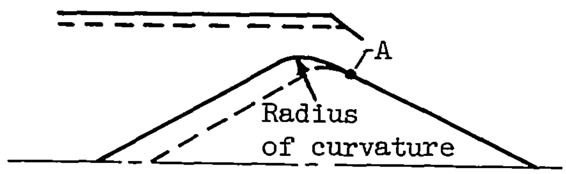
Nozzle Configurations

The 34 plug nozzle configurations investigated are listed in table I along with the dimensions of the various parts. Diagrams and dimensions of the various plugs used in these configurations are shown in figure 1. Exploded views of two typical configurations, one with a contoured plug and the other with a conical plug are shown in figure 2.

Plug design. - Two basic contoured-plug nozzles were investigated. The aft sections (downstream of the throat) of these nozzles were designed for pressure ratios of 9.3 and 14 (configurations 1 and 2) by the method of characteristics (see ref. 4) so that no overexpansion would occur on the plug surface at the design pressure ratio. No boundary-layer correction was applied, and the tail of the plug was cut off at a small diameter to reduce the length. The plug coordinates for these configurations are shown in figure 1(a)(plugs a and b).

Conical-plug nozzles, designed for pressure ratios of approximately 8 to 20, were investigated with plug angles of 40°, 50°, 60°, and 80° (configurations 3 to 10). The dimensions of the conical plugs are shown in figure 1(b) (plugs g to n).

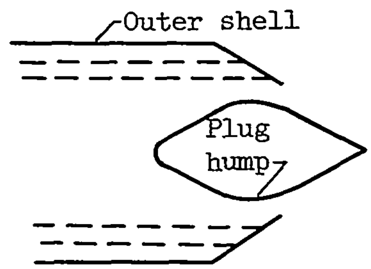
The effect of decreasing the maximum diameter of the conical and contoured plugs was investigated with configurations 1, 12, 13, and 14. As shown by sketch (a), reducing the maximum diameter necessitated decreasing the radius of curvature upstream of the throat, because the plug diameter at point A was held constant for all configurations. The smaller maximum plug diameter also allowed a smaller-diameter outer shell at the plug hump. The plug dimensions of these configurations are shown in figure 1 (plugs a, k, o, and d).



Sketch (a).

The effect of shortening the the length of the contoured plug upstream of the throat was investigated with configurations 14, 15, and 16 (plugs d, e, and f, fig. 1(a)).

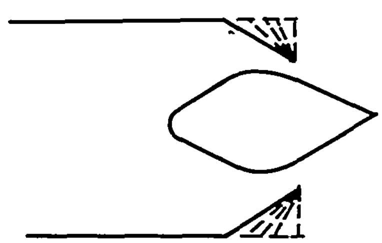
Outer-shell design. - The effect of varying Mach number at the plug hump of both contoured- and conical-plug nozzles was studied with configurations 5, 11, 14, 17, 18, and 19. The hump Mach number was varied by changing the outer-shell diameter as shown by the dashed lines in sketch (b). The hump Mach number of the contoured-plug nozzles was varied from 0.25 to 0.70, and that of the conical-plug nozzles was varied from 0.25 to 1.00.



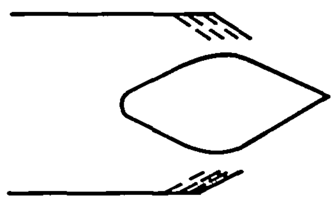
Sketch (b).

The effect of the outer-shell lip angle α on the performance of the contoured- and conical-plug nozzles was determined with configurations 5, 11, 12, and 20 to 24. The outer-shell angle of the conical plugs was varied from 15° to 90° and that of the contoured plugs from 15° to 30° (sketch (c)).

The effect of outer-shell exit position on the performance of conical-plug nozzles was studied with configurations 18 and 25 to 29. The outer-shell exit position was varied from the hump of the plug to a point downstream of where the conical section becomes



Sketch (c).



Sketch (d).

tangent to the curved portion of the plug (shown schematically in sketch (d)).

Throat-area variation. - The throat area of a contoured-plug nozzle was varied by two methods. The first method consisted of a series of outer shells with various lip angles 3843 that simulate an iris-type outer shell. The second method consisted of inserting spool pieces (fig. 2) of various lengths, which changed the position of the outer-shell exit relative to the plug, to simulate a translatable-type outer shell.

The effect of area variation with a simulated iris outer shell was determined with configurations 30 to 32 and with a translatable outer shell with configurations 31, 33, and 34.

Installation

The nozzles were installed in a test chamber, which was connected to the laboratory compressed-air and altitude-exhaust facilities as shown in figures 3 and 4. The nozzles were bolted to a mounting pipe, which was freely suspended by four flexure rods that were connected to the bedplate. Pressure forces acting on the nozzle and mounting pipe, both external and internal, were transmitted from the bedplate through a flexure-plate-supported bell crank and linkage to a balanced-air-pressure diaphragm force-measuring cell. Pressure differences across the nozzle and mounting pipe were maintained by labyrinth seals around the mounting pipe, which separated the nozzle inlet air from the exhaust. The space between the two labyrinth seals was vented to the test chamber. This decreased the pressure differential across the second labyrinth and prevented a pressure gradient on the outside of the diffuser section due to an air blast from the labyrinth seal.

Instrumentation

Pressures and temperatures were measured at the various stations indicated in figure 3. Total- and wall static-pressure measurements at station 1 were used to compute inlet momentum, and total- and static-pressure measurements (stream and wall static) at station 2 were used to compute air flow. Total pressure and temperature were measured at the nozzle inlet (station 3). Ambient exhaust pressure was provided at station 0, and a static-pressure survey was made on the outside walls of the bellmouth inlet. Wall static pressures were measured along the surfaces of each of the plugs from maximum diameter to downstream tip.

PROCEDURE

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Performance data for each configuration were obtained over a range of nozzle pressure ratios at a constant air flow. The nozzle pressure ratio was varied from about 1.5 to the maximum obtainable. Maximum pressure ratio varied from configuration to configuration because of the varying throat areas and the limited air-handling capacity of the air supply and exhauster equipment.

The thrust coefficient was calculated by dividing the actual jet thrust by the ideal jet thrust. The actual jet thrust was computed from the force measured by the balanced-air-pressure diaphragm and from pressure and temperature measurements made throughout the setup. The ideal jet thrust is defined as the product of the measured mass flow and the isentropic jet velocity based on the nozzle pressure ratio and the inlet temperature. To simplify the use of the air-flow data, the throat area used in the calculation of the air-flow parameter is defined as the annulus area between the outer-shell exit and the plug in a plane perpendicular to the nozzle axis. The symbols used in this report are defined in appendix A, and the methods of calculation are given in appendix B.

RESULTS AND DISCUSSION

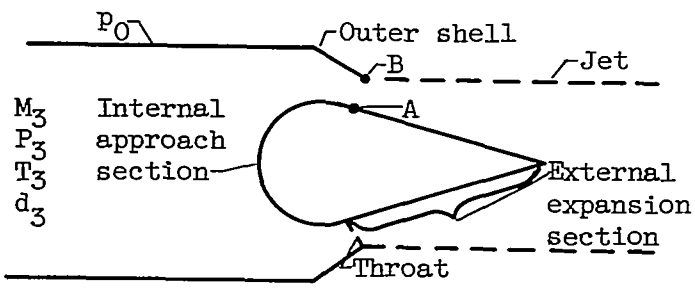
Typical Plug Nozzle Performance and Principles of Operation

The convergent-plug nozzle has the advantage of having high thrust coefficients over a wide range of pressure ratios. This is illustrated in figure 5, where the thrust coefficients for a convergent-plug nozzle and a convergent-divergent nozzle are compared over a range of pressure ratios. The difference in the design pressure ratios of these nozzles is not enough to have much effect on the results of this comparison. At the design pressure ratio the peak thrust coefficient of the plug nozzle is the same as that of the convergent-divergent nozzle. At pressure ratios below design the thrust coefficient of the plug nozzle is insensitive to pressure ratio, while that of the convergent-divergent nozzle decreases rapidly because of overexpansion losses. In general, the supersonic expansion of the gas in a plug-type nozzle takes place from the outer-shell lip and is controlled by the back pressure. Therefore, the plug nozzle does not have the large shock losses associated with the confined expansion section of the convergent-divergent nozzle at pressure ratios below design.

It is very important that all of the expansion waves emanate from the outer-shell lip if serious performance losses are to be avoided. For all of the expansion waves to emanate from the outer-shell lip, the throat must extend from the outer-shell lip to a point on the plug downstream of the point where the curved section at the plug hump becomes tangent to the external expansion section (see sketch on fig. 6). When the throat is located on the curved section of the plug the thrust coefficient decreases, because the pressures on the plug surface will decrease as a result of some of the expansion occurring around the curved section. Moving the throat of a conical plug nozzle from the point of tangency to the plug hump reduces the thrust coefficient from 0.97 to 0.90, as shown in figure 6. The configurations used to obtain these data had various outer-shell lip angles, but this has no effect on the nozzle thrust coefficient, as is shown in a later section of the report. 3843

Nozzle Design Procedure and Design Variables

When a nozzle is being designed for a given application, the nozzle inlet and ambient conditions are usually known. These include Mach number, total pressure, temperature, diameter, and ambient static pressure, as shown in sketch (e). The nozzle throat area and expansion ratio can then be determined. They fix the exit area of the outer shell or the jet diameter (at point B in sketch (e)) if the jet is assumed to expand axially. The diameter of the plug at the throat (indicated by A) is established by the throat area.



Sketch (e).

As mentioned previously, the throat should extend between the outer-shell lip and same point on the plug. The exact location of this point on the plug depends somewhat on the contour selected for the external expansion section of the plug. There are many design variables to consider in designing the various parts of the nozzle. These include the shape of the external expansion section of the plug, which may be either conical or contoured, the shape of the internal approach section where plug length and radius of curvature may be varied, the Mach number at the hump of the plug, and the outer-shell lip angle. In the following section the effect of the various design variables on nozzle performance is discussed.

Effect of Design Variables on Nozzle Performance, Size, and Weight

An exhaust nozzle should have high efficiency. It should also be as compact as possible, so that weight, cooling surface, and external drag are at a minimum. Therefore, it is necessary to know the optimum design for each geometric variable in order to obtain the best performance with the smallest size nozzle.

External plug shape. - The external plug shape affects the thrust coefficient, the weight, and the surface to be cooled. The effect of the conical plug angle ε on peak thrust coefficient is shown in figure 7, where the peak thrust coefficients for conical-plug nozzles designed for pressure ratios of approximately 8 and 20 are plotted against plug included angle. It can be seen that peak thrust coefficient is sensitive to plug angle and that the optimum angle varies with design pressure ratio. The conical-plug angle for best performance increases from 60° to 80° as the design pressure ratio is varied from approximately 8 to 20. The level of the peak thrust coefficients of contoured-plug nozzles (designed by the method of characteristics to discharge the flow axially), designed for pressure ratios of 9.3 and 14, is indicated in figure 7 by dashed lines. The peak thrust coefficients of the contoured-plug nozzle are about 1 percentage point higher than the best that can be obtained with a conical-plug nozzle.

The cooling area and weight of a contoured plug would be about the same as those of the 60° conical plug, since they both have the same surface area.

Internal plug shape. - The design of the internal portion of the plug can affect the nozzle thrust coefficient, size, weight, and external drag. The external drag referred to here is caused by skin friction, which varies with over-all nozzle diameter. The two geometric variables governing the shape of this part of the plug are the radius of curvature upstream of the throat and the length. As the radius of curvature of the plug is decreased, the maximum plug diameter decreases. This allows the over-all diameter of the nozzle to decrease. Varying the maximum plug diameter of both the contoured and conical plugs by changing the radius of curvature upstream of the throat had no effect on the nozzle thrust coefficient. This is shown in figure 8, where thrust coefficient is plotted against nozzle pressure ratio.

The rate of curvature of the contoured plug was changed considerably, which resulted in a 40-percent decrease in the plug cross-sectional area at the hump (see plugs a and d, fig. 1(a)). The cross-sectional area at the hump of the conical plug was varied 17 percent by decreasing the radius of curvature from 3 inches to 1 inch (see plugs K and O, fig. 1(b)).

Very short plug lengths and abrupt approach sections can be used without adversely affecting the performance of the nozzle. For example, an 81-percent reduction in the length of the internal section of the contoured plug causes only a 1/2-percent drop in thrust coefficient, as shown in figure 9.

Hump Mach number. - The limiting value of the hump Mach number that affects nozzle performance is important, because it defines the minimum size of the nozzle if the minimum plug size at the hump is selected. Since it affects nozzle size, it will also affect weight and external drag.

Hump Mach numbers up to 1.0 have no effect on the performance of 3843
the conical-plug nozzle. This is shown in figure 10(a), where thrust coefficient is plotted against nozzle pressure ratio. Hump Mach number does, however, affect the performance of the contoured-plug nozzle. At a hump Mach number of 0.70 the nozzle thrust coefficient decreased about 1/2 percent below that of nozzles with lower hump Mach numbers (fig. 10(b)). This reduction in thrust coefficient was due to an expansion of the flow around the curved portion of the plug just upstream of the throat. This caused pressures on the plug surface to drop below those which would naturally occur if the expansion were controlled from the lip. This harmful expansion did not occur with the conical plug, because it had a larger radius of curvature at the hump than the contoured plug. The performance of the contoured plug would not have decreased at the higher hump Mach numbers if the radius of curvature upstream of the throat had been slightly larger.

Outer-shell lip angle. - Lip angle α can have a large effect on the external base drag of an aircraft installation. As the lip angle is increased the external airstream must turn through a larger angle; this results in either a lower pressure along the outer-shell lip and a higher base drag (see ref. 5). It is also possible for the lip angle to have an effect on thrust coefficient. The effect of lip angle on the thrust coefficient of a conical-plug nozzle is shown in figure 11 (a), where thrust coefficient is plotted against pressure ratio. The theoretical lip angle that would be required to discharge the flow axially is about 25° for the nozzles shown in the figure. However, variations in the lip angle from 15° to 90° had no effect on the thrust coefficient of a conical-plug nozzle.

Lip angle did, however, affect the thrust coefficient of the contoured-plug nozzle, as shown in figure 11(b). A decrease in lip angle from 30° to 15° decreased the thrust coefficient about 1 percent. The lower lip angle caused the throat to shift upstream from the outer-shell exit to a minimum area formed by the hump of the plug and the outer shell. The nozzle suffers from high overexpansion losses at pressure ratios below design because of the slight divergent section that was formed between the throat and outer-shell exit.

Since lip angle has no effect on the performance of a conical-plug nozzle, it is possible that, if the lip angle of this particular contoured plug nozzle were limited to 20° so as to maintain the throat at the outer-shell exit, the thrust coefficient would be unchanged from that of the nozzle with a 30° lip angle.

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Nozzle Size for Maximum Performance at Design Condition and

Performance Penalties for Size Reduction

For any given design pressure ratio the minimum nozzle size and maximum nozzle-inlet Mach number are fixed if maximum internal performance is to be obtained. Applications arise, however, where a nozzle must have an inlet Mach number higher than that which gives maximum internal performance; and, consequently, the over-all nozzle size must be decreased. This results in a lower design pressure ratio and consequently underexpansion losses. The relation between nozzle size, inlet Mach number, and the penalties for off-design conditions are presented in figure 12. The data from the previous section were used to design the minimum-size conical-plug nozzle for each condition shown.

In figure 12(a) nozzle thrust coefficient is plotted against inlet Mach number for nozzles operating at pressure ratios of 5, 15, and 25. The maximum thrust coefficient is obtained, of course, when each nozzle is operated at its design pressure ratio, as indicated by the design points. As shown by the curves, the inlet Mach numbers are 0.16, 0.22, and 0.43 for nozzles that are on design at pressure ratios of 25, 15, and 5, respectively. If it is necessary to go to higher inlet Mach numbers with the throat area remaining constant, the size of the plug must be decreased; then the nozzle becomes underexpanded, with a resultant loss in thrust coefficient. The extreme limit is reached at an assumed inlet Mach number of 0.9, where the plug has vanished and a simple convergent nozzle results.

Nozzle size (expressed as a ratio of maximum nozzle cross-sectional area to throat area, A_N/A_{th}) is plotted against inlet Mach number in figure 12(b) for the nozzles of figure 12(a). For example, when a nozzle is operating on design at a pressure ratio of 25, the value of A_N/A_{th} is 3.63 and the thrust coefficient is 0.97 (line A). If the inlet Mach number is increased to 0.4 for this same nozzle pressure ratio, the value of A_N/A_{th} decreases to 1.57, and the thrust coefficient drops to 0.92 (line B).

In the range of pressure ratios where a convergent-divergent located exhaust nozzle would be used, the exit area is generally the largest cross-sectional area of the nozzle. Therefore, the relative size of a plug nozzle and a convergent-divergent nozzle can be obtained by comparing the ratio of the maximum cross-sectional area to the throat area (A_N/A_{th}) of the plug nozzle, with the expansion ratio (A_e/A_{th}) of the convergent-divergent nozzle. This comparison shows that, for the same design pressure ratio, the plug nozzle is about 10 percent larger in cross-sectional area than the convergent-divergent nozzle. 3843

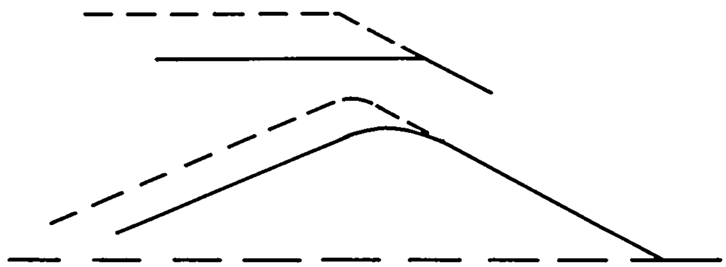
Throat-Area Variation

The throat area of a plug nozzle can be varied by one of two methods, using an iris-type outer shell or translating the outer shell or the plug. A nozzle with a simulated iris outer shell has better performance characteristics over a range of throat areas than one with a translatable outer shell. This is shown in figure 13 where the thrust coefficient is plotted against nozzle pressure ratio for a range of relative throat areas. Relative throat area is defined as the ratio of the effective throat area of the nozzle in question to the effective throat area of configuration 31. (The choice of configuration 31 to show the relative change in throat area was completely arbitrary.) The effective throat area is the theoretical throat area for choked flow computed from measured air flow and nozzle-inlet total pressure and temperature.

Varying the throat area with an iris-type outer shell has a small effect on peak thrust coefficient (fig. 13(a)). In contrast to the performance of the iris-type outer shell, the peak thrust coefficient with the translatable outer shell varied from 0.98 to 0.95 over the range of relative throat areas. Translating the outer shell toward the hump of the plug lowers the peak thrust coefficient when the outer-shell exit is located on the curved portion of the plug. The reason for this decrease in thrust coefficient was discussed earlier. This condition also increases the over expansion losses at the low pressure ratios. As the throat area is increased by either of the two methods, the peak thrust coefficient occurs at lower pressure ratios because of the decrease in expansion ratio.

A cross plot of the data of figure 13 at pressure ratios of 4.5 and 10 is shown in figures 14(a) and (b), respectively. The thrust coefficients of the iris outer shell are almost independent of throat-area variation at both nozzle pressure ratios of 4.5 and 10. At a nozzle pressure ratio of 4.5, the thrust coefficients obtained with the translatable outer shell are lower than those with the iris outer shell at the low relative throat areas because of greater overexpansion losses. At a nozzle pressure ratio of 10, the thrust coefficients of the translatable outer shell are lower than those of the iris outer shell at both the low and high relative throat areas. The thrust coefficients of the translatable outer shell were lower at the high relative throat areas because of higher underexpansion losses. The reason for these greater underexpansion losses is shown in figure 14(c). The expansion ratio of an iris-outer-shell nozzle is less sensitive to area variation than that of a translatable-outer-shell nozzle.

To avoid serious losses in performance with the translatable outer shell the throat must always be located downstream of the curved section of the plug hump. Therefore, a translatable-outer-shell nozzle that is designed for the maximum throat area required by a given flight plan must have a larger outer shell and plug than an iris-type nozzle. This is shown schematically for a conical plug nozzle by sketch (f).



Sketch (f).

The solid lines represent a nozzle that is designed for a given pressure ratio and maximum throat area. The minimum outer-shell diameter is selected and the throat is located just downstream of the curved portion of the plug. Smaller throat areas with an iris nozzle can be obtained without performance penalties. In order to reduce the throat area with a translatable outer shell without performance losses, the size of the plug and outer shell must be increased to the envelopes shown by the dotted lines. This increase would position the curved section of the plug further upstream and the throat would remain on the straight section of the plug as the outer shell was translated upstream. Therefore, for a given outer-shell size, the iris-type outer shell provides a greater range of throat areas without a serious penalty in performance.

Air-Flow Parameter

The corrected-air-flow parameter $w\sqrt{\theta}/A_{fl}\delta$, which is constant for each configuration above a pressure ratio of 2, is listed in table I for all configurations. For values below a pressure ratio of 2, see references 1 to 3. The theoretical value of the air-flow parameter for choked flow is 0.344 pounds per second per square inch of flow area. The flow coefficients (ratio of experimental to theoretical air-flow parameter) for these configurations vary from 0.80 to 0.985 when the flow is choked. In order to simplify the use of the air-flow data, the throat area used in the calculation of the air-flow parameter is defined as the annulus area between the outer-shell exit and the plug in a plane perpendicular to the nozzle axis (flow area A_{fl} listed in table I). For most configurations this area is greater than the actual physical throat area (see A_{th} in table I), and, consequently, the flow coefficients were lower than those for a simple convergent-divergent nozzle.

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SUMMARY OF RESULTS

Convergent-plug nozzles were investigated over a range of pressure ratios from 1.5 to 32 to determine the effect of geometrical design variables on internal performance.

The plug nozzle has peak thrust coefficients as high as those obtainable with a convergent-divergent nozzle at the design pressure ratio. At pressure ratios below design, the thrust coefficient of the plug nozzle is relatively insensitive to pressure ratio, while that of the convergent-divergent nozzle decreases rapidly because of overexpansion losses.

Contoured-plug nozzles designed to give parallel exit flow have peak thrust coefficients of approximately 0.98. At pressure ratios below design the thrust coefficient varies only from 0.96 to 0.98.

The simple conical-plug nozzles have about the same performance trends as the contoured-plug nozzles, but the thrust coefficient is about 1 percentage point lower. The plug angle for best performance increases from 60° to 80° as the design pressure ratio is increased from approximately 8 to 20.

Decreasing the maximum diameter of the plug by decreasing the radius of curvature upstream of the throat has no effect on nozzle performance. The length of the plug upstream of the throat can be varied over a wide range without adversely affecting the performance of the nozzle. Therefore, very short lengths and abrupt approach sections can be used.

Outer-shell lip angles from 15° to 90° (referenced to nozzle axis) and Mach numbers at the plug hump up to 1.0 had no effect on the performance of the conical-plug nozzle. As lip angle is made shallower a condition is approached where the throat shifts from the outer-shell exit to a minimum area formed by the plug hump and the outer shell. With the particular contoured-plug nozzle that was investigated this occurred with a 15° outer-shell angle. High Mach numbers at the hump of the plug (0.70) have a small effect on the performance of the contoured-plug nozzle, although this condition can probably be relieved by increasing the radius of curvature of the plug upstream of the throat to values higher than those used during the tests.

This discussion on the outer-shell lip angle has only considered the internal performance of the nozzle. In selecting the proper lip angle for a given application, the external flow would also have to be considered.

The throat of the plug nozzle must always be located downstream of
3843 the point where the curved section at the hump of the plug becomes tangent to the expansion section. For example moving the throat of a conical plug nozzle from this tangency point to the plug hump reduced the peak thrust coefficient from 0.97 to 0.90.

For the same design pressure ratio a plug nozzle is about 10 percent larger in cross-sectional area than a convergent-divergent nozzle. This value was obtained by comparing the ratio of the maximum cross-sectional area to the throat area of a plug nozzle with the expansion ratio of the convergent-divergent nozzle.

It was found that the best method of varying the throat area of a convergent-plug nozzle was with an iris outer shell. For a given size outer shell and plug, the iris outer shell provides higher thrust coefficients over a greater range of throat areas than a translatable outer shell.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland 11, Ohio, August 6, 1956

APPENDIX A

SYMBOLS

A	inside area, sq in.
A_{fl}	flow area (annulus between outer-shell exit area and plug in plane perpendicular to plug axis), sq in. 3843
A_L	pipe area under labyrinth seal, sq in.
A_N	maximum cross-sectional area of plug nozzle, sq in.
A_r	relative throat area, sq in.
A_s	exit area of outer shell, sq in.
A_{th}	throat area, sq in.
$\overline{A}_{th}$	effective throat area for choked flow computed from mass flow, total pressure, and temperature, sq in.
C_T	thrust coefficient
F	thrust, lb
F_d	balanced-air-pressure-diaphragm reading, lb
g	acceleration due to gravity, 32.17 ft/sec^2
l_s	distance from maximum diameter of plug to outer-shell exit, in.
P	total pressure, lb/sq ft
p	static pressure, lb/sq ft
p_{bm}	integrated static pressure acting on outside of bellmouth inlet to station 2, lb/sq ft
R	gas constant, 53.35 ft-lb/(lb)(R^o) for air
T	total temperature
V	velocity, ft/sec

w_a	air flow, lb/sec
w_f	engine fuel flow, lb/sec
α	outer-shell lip angle, deg
β	angle between upstream plug surface and center line, deg
γ	ratio of specific heats
δ	ratio of total pressure at nozzle inlet to absolute pressure at NACA standard sea-level conditions
ε	conical-plug included angle at downstream tip, deg
θ	ratio of total temperature at nozzle inlet to absolute temperature at NACA standard sea-level conditions
$\frac{w_a\sqrt{\theta}}{A_{fl}\delta}$	corrected-air-flow parameter, (lb/sec)/(sq in.)

Subscripts:

e	nozzle exit
id	ideal
j	jet
0	exhaust or ambient
1	bellmouth inlet
2	diffuser inlet
3	nozzle inlet

APPENDIX B

METHODS OF CALCULATION

Air Flow 3843

The nozzle air flow was calculated as

$$w_{a,2} = \frac{p_2 A_2}{144\sqrt{RT_3}}\sqrt{\frac{2g\gamma}{\gamma-1}\left[\left(\frac{P_2}{p_2}\right)^{\frac{\gamma-1}{\gamma}} - 1\right]\left(\frac{P_2}{p_2}\right)^{\frac{\gamma-1}{\gamma}}} \tag{B1}$$

where γ was assumed to be 1.4.

Thrust

The jet thrust was defined as

$$F_j = \frac{w_{a,2}}{g}\overline{V}_e + \frac{A_s}{144}(\overline{p}_e - p_0) \tag{B2}$$

where $\overline{V}_e$ and $\overline{p}_e$ are effective values. The actual jet thrust was calculated from

$$F_j = \frac{w_{a,2}}{g}V_1 + p_1\frac{A_1}{144} - p_{bm}\frac{A_1}{144} + \frac{A_L}{144}(p_{bm} - p_0) - F_d \tag{B3}$$

where F_d was obtained from balanced-air-pressure measurements.

The ideally available jet thrust, which was based on measured mass flow, was calculated as

$$F_{j,id} = w_{a,2}\sqrt{\frac{2R}{g}\frac{\gamma}{\gamma-1}T_3\left[1 - \left(\frac{p_0}{P_3}\right)\right]^{\frac{\gamma-1}{\gamma}}} \tag{B4}$$

Thrust Coefficient

The thrust coefficient is defined as the ratio of the actual to the ideal jet thrust:

$$C_T = \frac{F_j}{F_{j,id}} \tag{B7}$$

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3. Krull, H. George, and Beale, William T.: Comparison of Two Methods of Modulating the Throat Area of Convergent Plug Nozzles. NACA RM E54L08, 1955.

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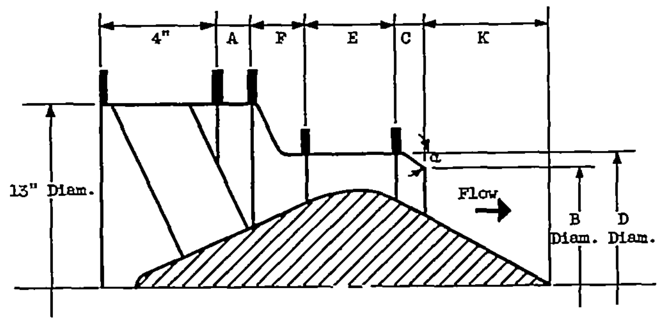

CD-4664

TABLE I. - CONFIGURATION DIMENSIONS

Configuration	Expansion ratio, A_s/A_{th}	Isentropic pressure ratio	Throat area, A_{th}, sq in.	Effective throat area, $\bar{A}_{th}$, sq in.	Flow area, A_{fl}, sq in.	Air-flow parameter, $\frac{w_a\sqrt{\theta}}{A_{fl}\delta}$, $\frac{\text{(lb/sec)}}{\text{sq in.}}$	A, in.	B, in.	C, in.	D, in.	E, in.	F, in.	K, in.	α	Plug
1	1.86	9.3	37.88	38.5	46.87	0.281	----	9.46	2.98	13	7.87	----	6.57	30°40'	a
2	2.33	14.0	39.38	40.16	50.66	.272	----	10.80	1.46	13	8.12	----	8.93	37°	b
3	1.73	8.2	35.70	34.60	36.78	.325	----	8.86	4.13	13	2.63	----	7.69	26°42'	g
4	1.71	8.1	36.06	34.20	38.06	.319	----	8.86	4.13	13	2.63	----	5.88	26°42'	i
5	1.56	6.7	39.60	37.61	40.58	.316	----	8.86	4.13	13	2.81	----	4.37	26°42'	k
6	1.76	8.5	34.95	36.30	41.22	.299	----	8.86	4.13	13	3.95	----	3.01	26°42'	m
7	2.86	19.5	33.30	31.29	33.74	.320	----	11.02	1.30	13	7.65	----	2.17	37°12'	h
8	2.91	20.2	32.71	33.02	35.07	.323	----	11.02	1.30	13	7.69	----	9.31	37°12'	j
9	3.11	22.5	30.60	-----	32.99	.327	----	11.02	1.30	13	7.67	----	7.71	37°12'	l
10	3.09	22.1	30.86	29.67	37.31	.273	----	11.02	1.30	13	7.57	----	5.10	37°12'	n
11	1.80	8.8	38.95	38.76	46.40	.286	----	9.46	2.98	13	8.07	----	6.48	30°42'	d
12	1.64	7.4	37.58	-----	40.74	.311	----	8.86	4.84	13	2.08	----	4.40	23°9'	k
13	1.64	7.4	37.60	36.12	40.72	.304	1.49	8.86	.57	9.43	3.15	1.90	4.36	26°25'	o
14	1.86	9.3	37.75	37.68	46.50	.278	2.12	9.46	1.29	11.0	6.65	1.00	6.60	30°45'	d
15	1.86	9.3	37.75	37.27	46.50	.275	----	9.46	1.29	11.00	7.37	1.00	6.62	30°45'	e
16	1.86	9.3	37.75	37.61	46.50	.277	----	9.46	1.29	11.00	7.31	1.00	6.61	30°45'	f
17	1.86	9.3	37.75	36.72	46.50	.280	.84	9.46	.62	10.20	7.77	1.90	6.6	30°45'	d
18	1.69	7.8	34.15	33.40	44.60	.259	1.09	8.58	1.00	9.72	3.15	1.90	4.39	35°46'	k
19	1.69	7.8	34.30	32.82	36.40	.309	1.09	8.58	1.00	9.43	3.15	1.90	4.39	35°46'	k
20	1.86	9.3	37.75	38.00	46.50	.281	----	9.46	6.6	13.00	4.53	----	6.47	15°	d
21	1.64	7.4	37.60	36.46	41.22	.301	----	8.86	2.12	13.00	4.02	----	4.34	44°18'	k
22	1.64	7.4	37.60	35.81	41.38	.293	----	8.86	1.03	13.00	5.90	----	4.32	63°25'	k
23	1.60	7.1	38.60	34.97	42.33	.280	----	8.86	0	13.00	6.98	----	4.22	90°	k
24	1.60	7.1	38.60	35.52	40.58	.301	1.00	8.86	1.07	9.43	3.15	1.90	4.35	14°20'	o
25	1.60	7.1	36.30	32.67	37.55	.300	2.04	8.58	0	9.72	3.14	1.90	4.37	90°	k
26	1.95	10.2	29.70	28.67	31.84	.308	.52	8.58	1.00	9.72	3.14	1.90	4.90	35°46'	k
27	2.06	11.2	32.50	31.05	32.64	.328	.03	9.24	.57	9.72	3.14	1.90	5.83	22°58'	k
28	2.19	12.5	30.60	28.70	30.54	.320	.03	9.24	0	9.72	3.14	1.90	6.40	90°	k
29	1.97	10.4	37.80	37.51	37.83	.337	.06	9.73	2.80	9.72	0	1.90	6.71	0°	k
30	1.88	9.5	34.66	34.25	40.16	.290	----	9.12	2.88	13.00	7.91	----	6.60	34°	c
31	1.80	8.8	38.98	-----	46.87	.289	----	9.46	2.98	13.00	7.91	----	6.48	30°40'	c
32	1.56	6.7	52.13	51.80	60.64	.301	----	10.18	3.18	13.00	7.91	----	6.28	24°	c
33	2.37	14.3	29.60	27.97	32.60	.293	----	9.46	2.98	13.00	6.77	----	7.62	30°40'	c
34	1.34	4.9	52.42	49.74	56.70	.301	----	9.46	2.98	13.00	8.80	----	5.50	30°40'	c

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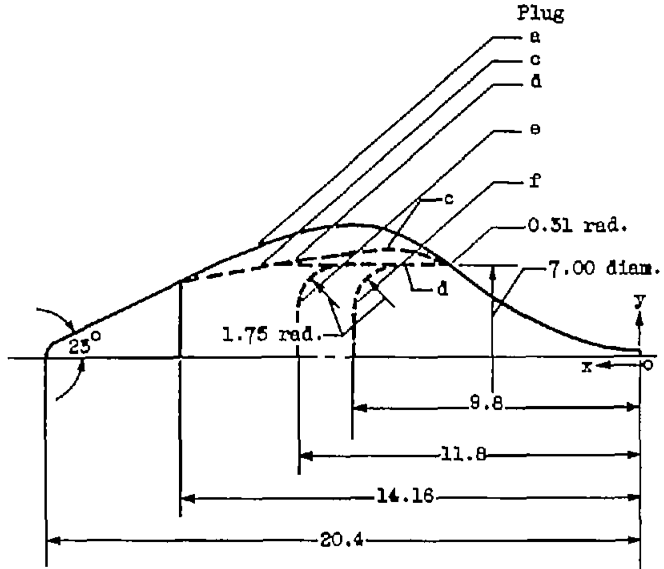
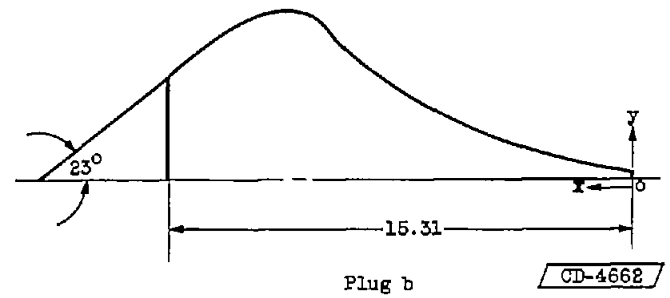


Plugs a, c, d, e, and f



Plug b

Plug a coordinates

x	y	x	y	x	y	x	y
0	0.18	3.50	1.09	7.00	3.14	10.50	4.50
.5	.25	4.00	1.30	7.40	3.52	11.00	4.42
1.00	.35	4.50	1.53	8.00	3.95	11.50	4.27
1.50	.47	5.00	1.79	8.50	4.20	12.00	4.05
2.00	.60	5.50	2.07	9.00	4.60	13.00	3.62
2.50	.74	6.00	2.39	9.50	4.42	14.00	3.17
3.00	.91	6.50	2.73	10.00	4.53	14.16	3.12

Plug b coordinates

x	y	x	y	x	y
0	0.20	8.00	2.90	12.00	5.14
1.00	.35	8.50	3.26	13.00	4.80
2.00	.55	9.00	3.67	14.00	4.12
3.00	.83	9.50	4.15	15.00	3.36
4.00	1.13	10.00	4.67	15.31	3.12
5.00	1.48	10.50	5.03		
6.00	1.86	11.00	5.18		
7.00	2.34	11.25	5.20		

Plug c coordinates

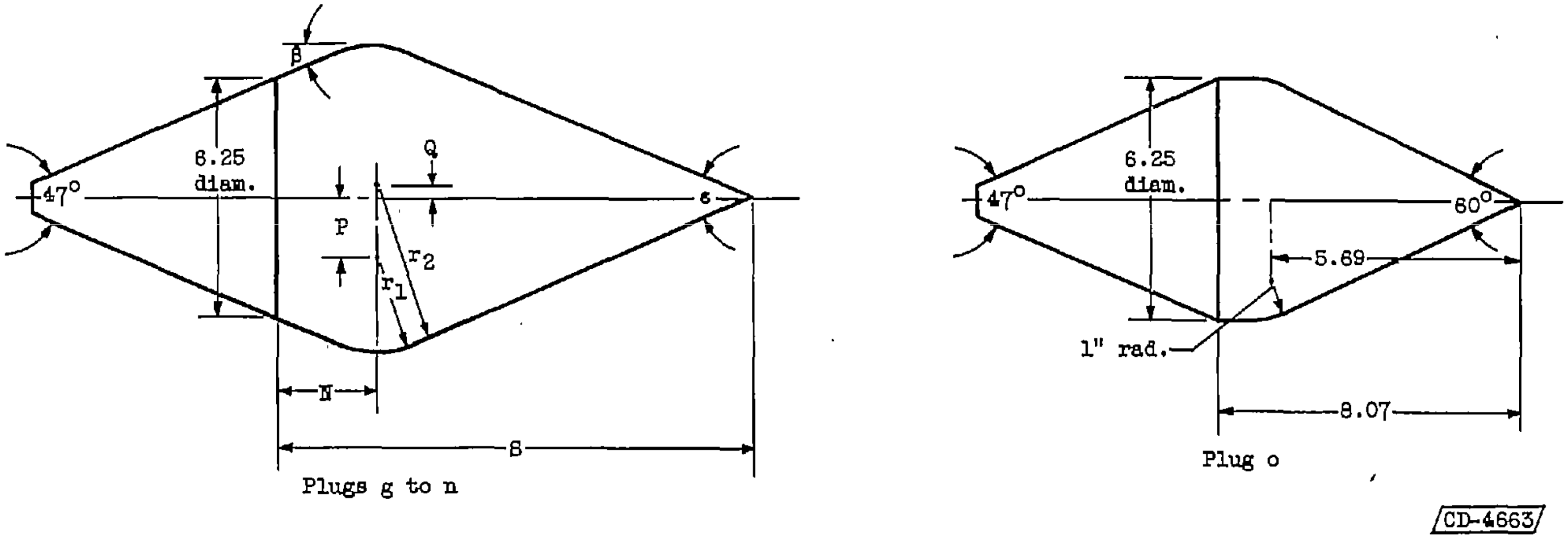
x	y	x	y
7	3.14	8.0	3.71
7.27	3.4	8.15	3.70
7.5	3.53	8.3	3.69
7.7	3.65	14.16	3.12

Plug d coordinates

x	y
7	3.14
7.27	3.4
7.4	3.47
7.5	3.50
10.3	3.50
14.16	3.12

(a) Contoured plugs (bodies of revolution).

Figure 1. - Plug configurations (all dimensions in inches).



Plug	ε	β	N	P	Q	r_1	r_2	S
g	40°	-	1.31	0.00	-	3.38	-	11.09
h	40°	30°	4.00	0.81	-	4.00	-	17.87
i	50°	-	1.30	-	.53	-	3.88	9.28
j	50°	28°	4.17	1.84	-	2.98	-	15.12
k	60°	-	1.35	0.22	-	3.20	-	8.07
l	60°	26°	4.16	2.36	-	2.52	-	13.25
m	80°	$23\frac{1}{2}°$	2.2	0.88	-	2.94	-	7.80
n	80°	35°	3.78	2.70	-	2.51	-	10.84

(b) Conical plugs (bodies of revolution).

Figure 1. - Concluded. Plug configurations (all dimensions in inches).

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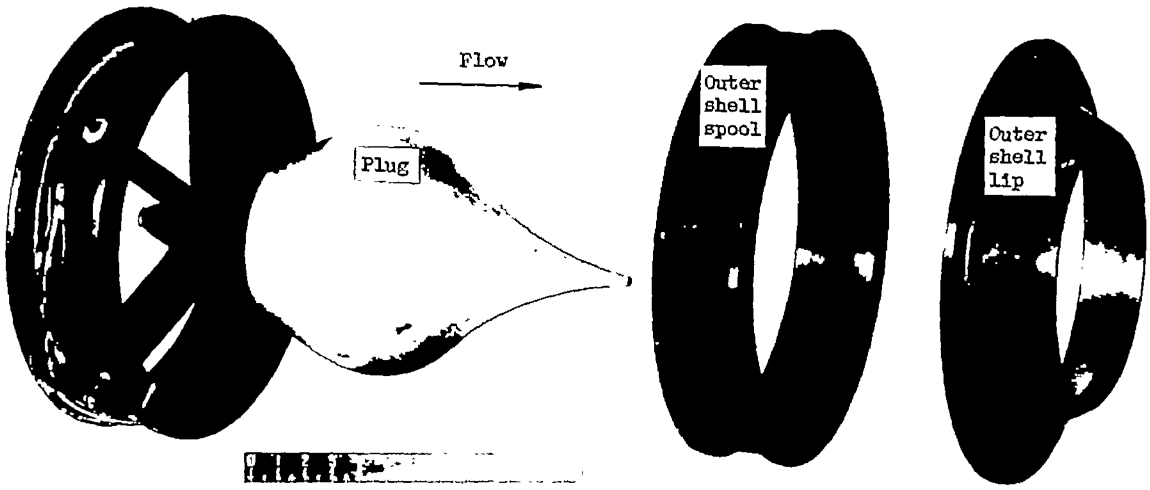
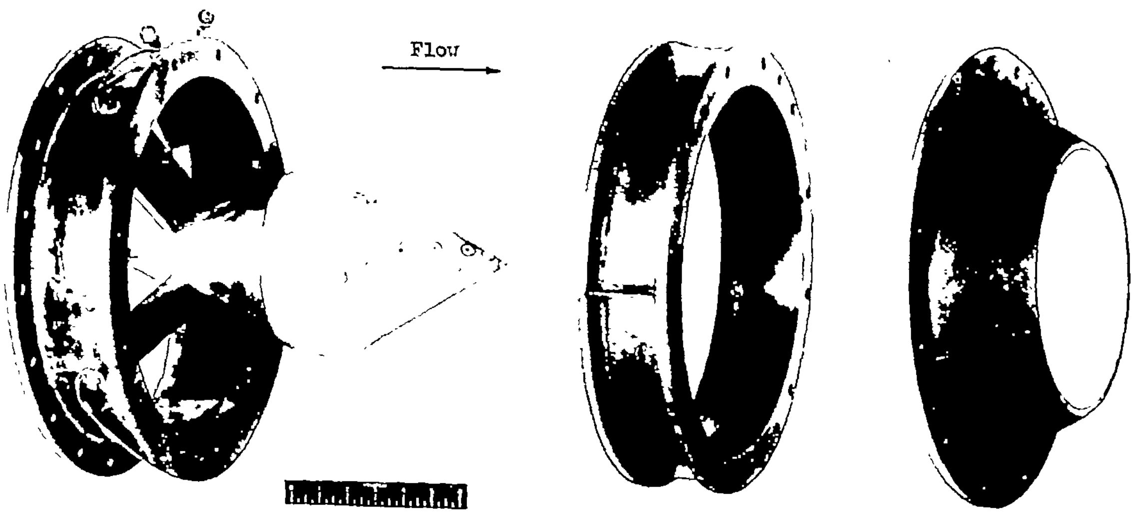


C-34356

(a) Contoured plug nozzle.



C-36298

(b) Conical plug nozzle.

Figure 2. - Exploded view of nozzles.

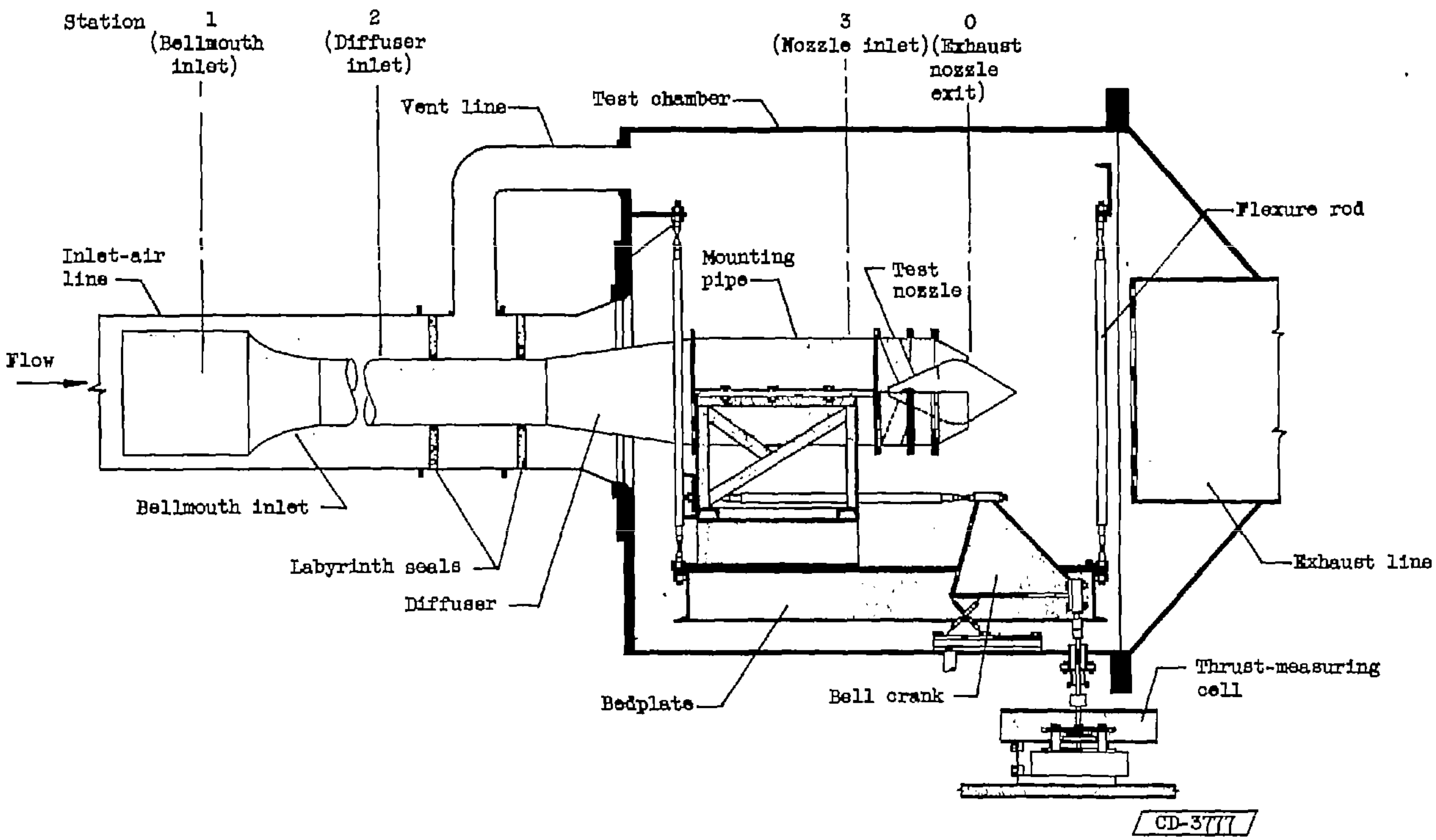


Figure 3. - Schematic drawing of nozzle in test chamber.

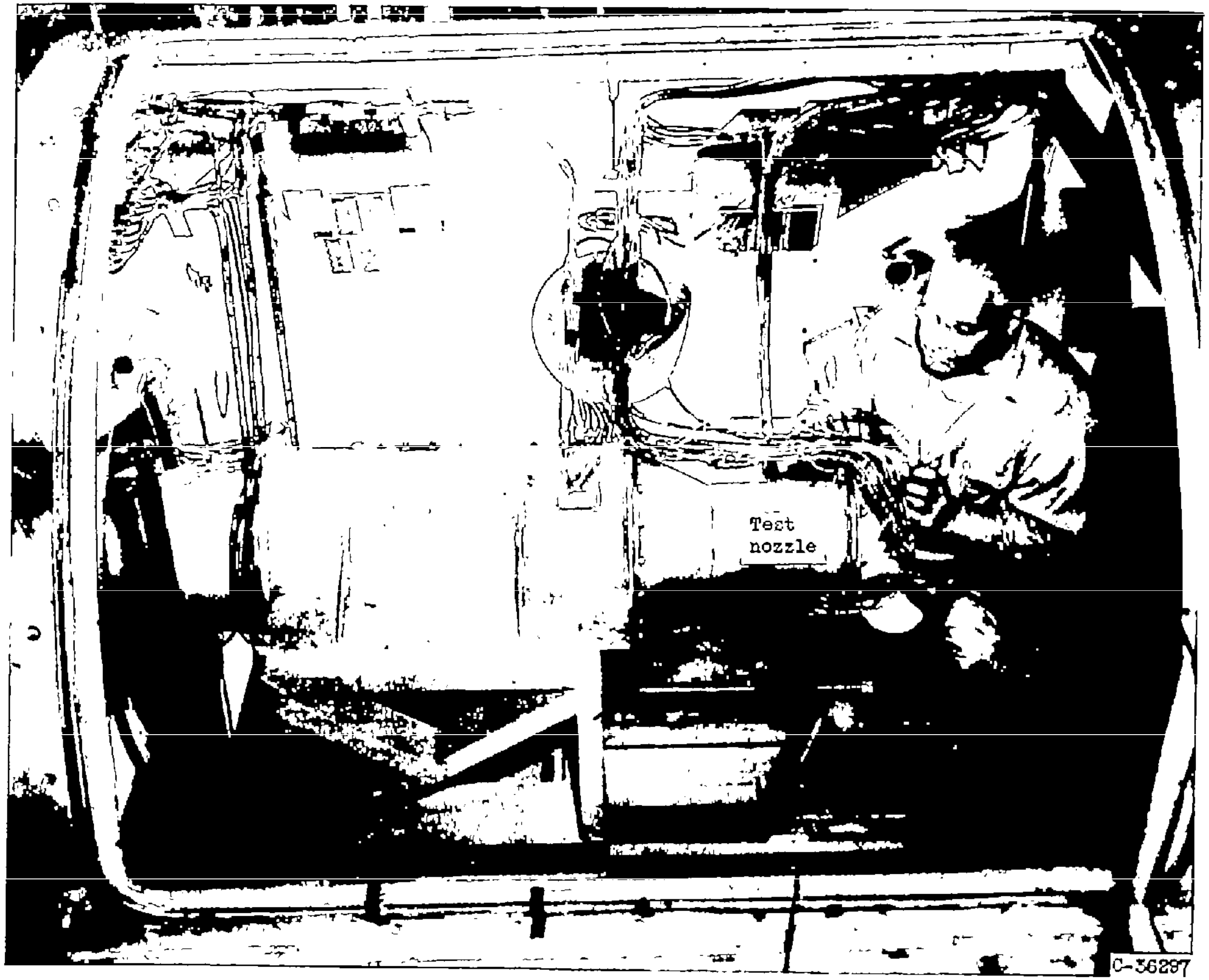


Figure 4. - Installation of nozzle in test chamber.

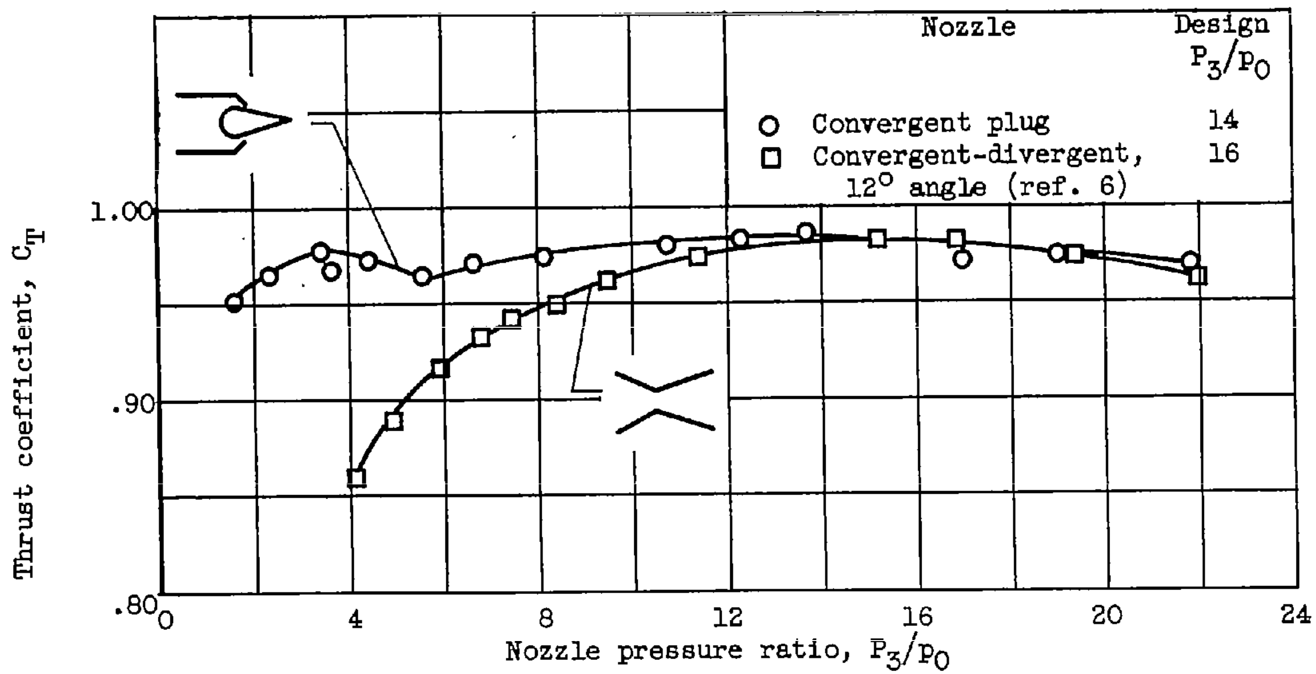


Figure 5. - Comparison of performance of convergent-plug and convergent-divergent nozzles.

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CT-4

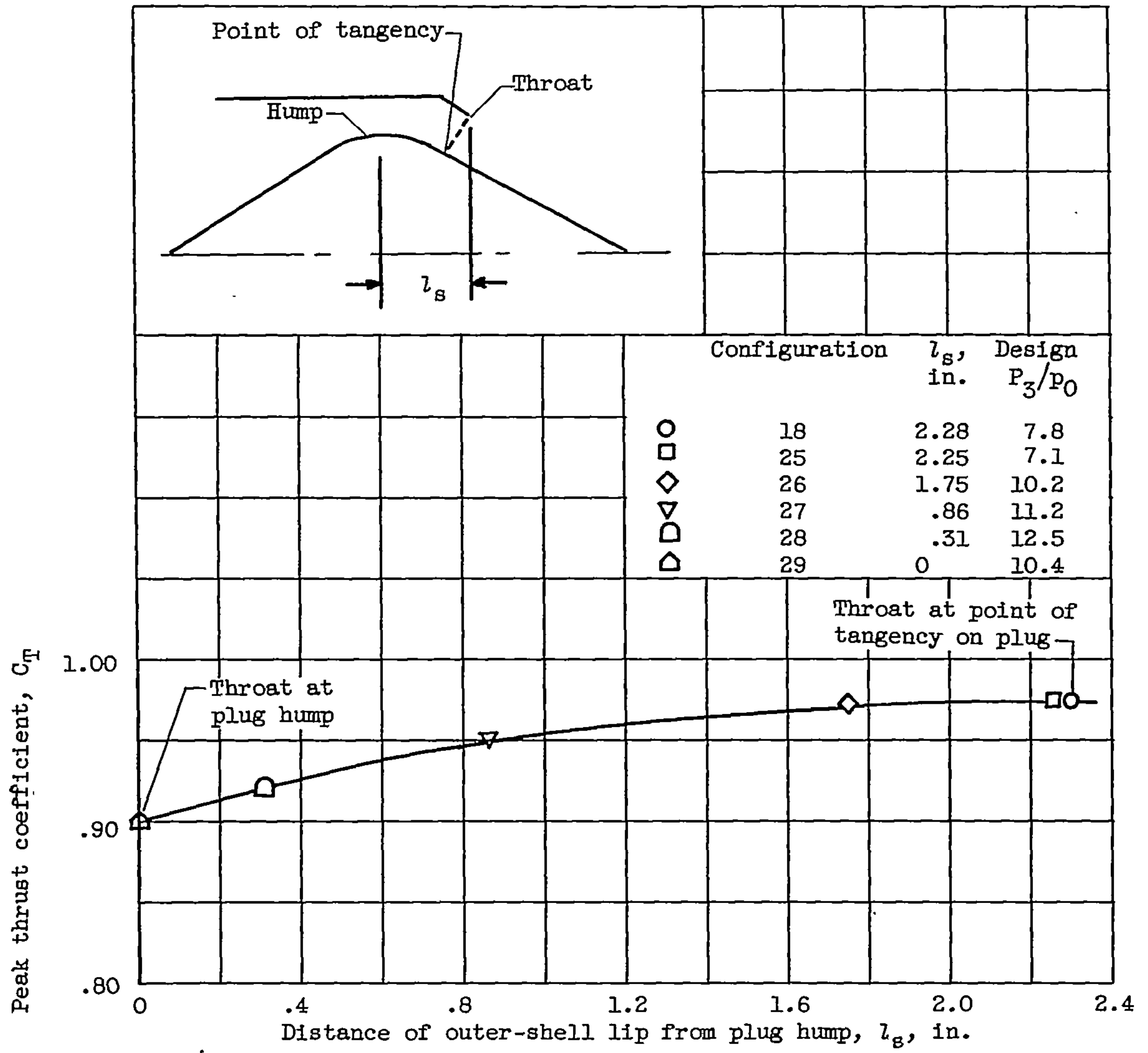

Figure 6. - Effect of outer-shell exit position on peak thrust coefficient.

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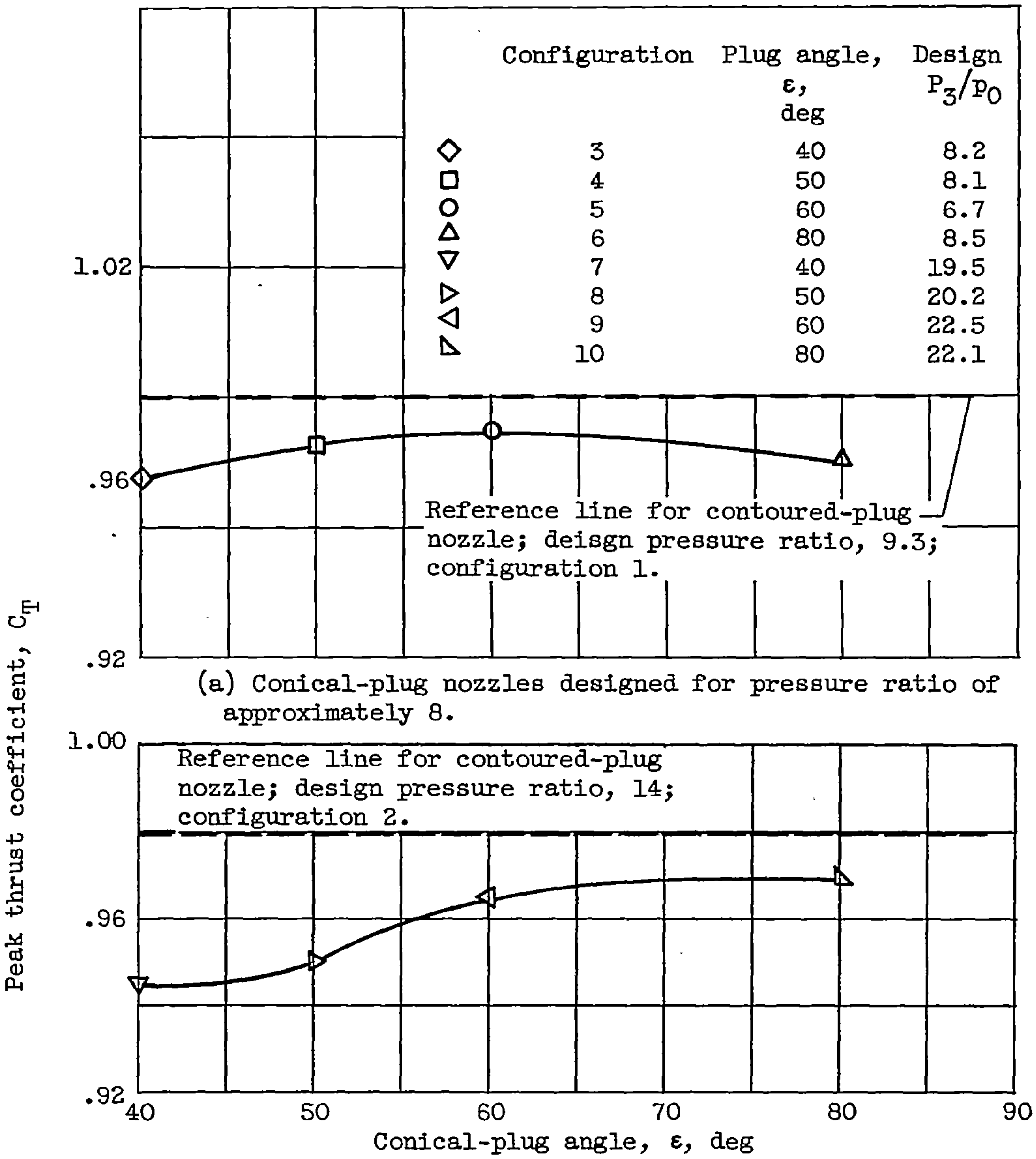

(a) Conical-plug nozzles designed for pressure ratio of approximately 8.

(b) Conical-plug nozzles designed for pressure ratio of approximately 20.

Figure 7. - Comparison of peak thrust coefficients of contoured-plug and conical-plug nozzles over range of conical-plug angles.

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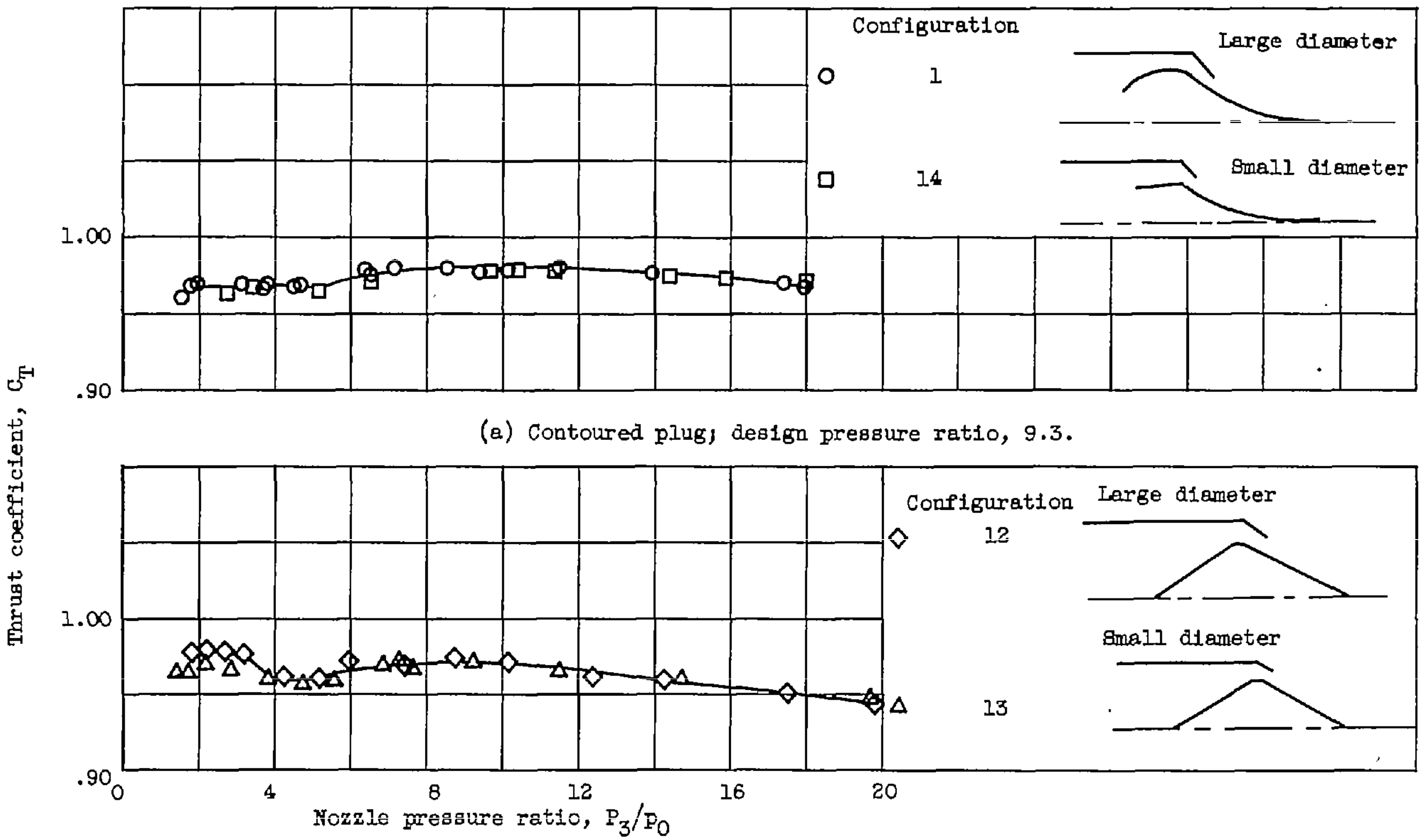

(a) Contoured plug; design pressure ratio, 9.3.

(b) Conical plug; design pressure ratio, 7.4.

Figure 8. - Effect of decreasing maximum plug diameter.

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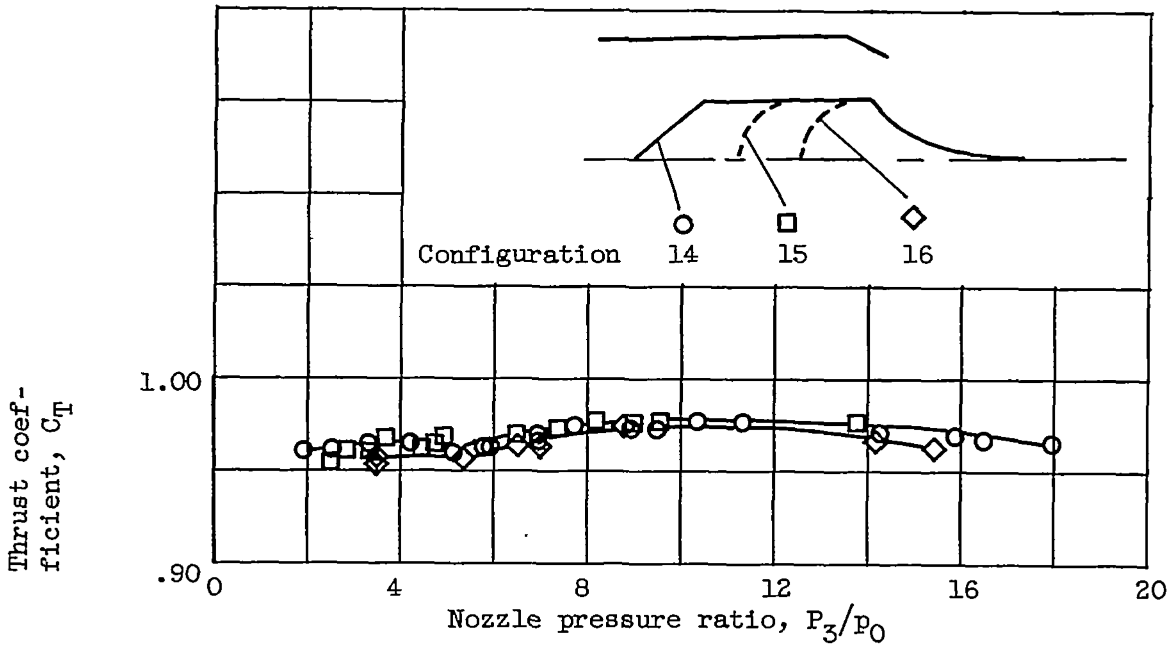

Figure 9. - Effect of decreasing length of plug upstream of throat.

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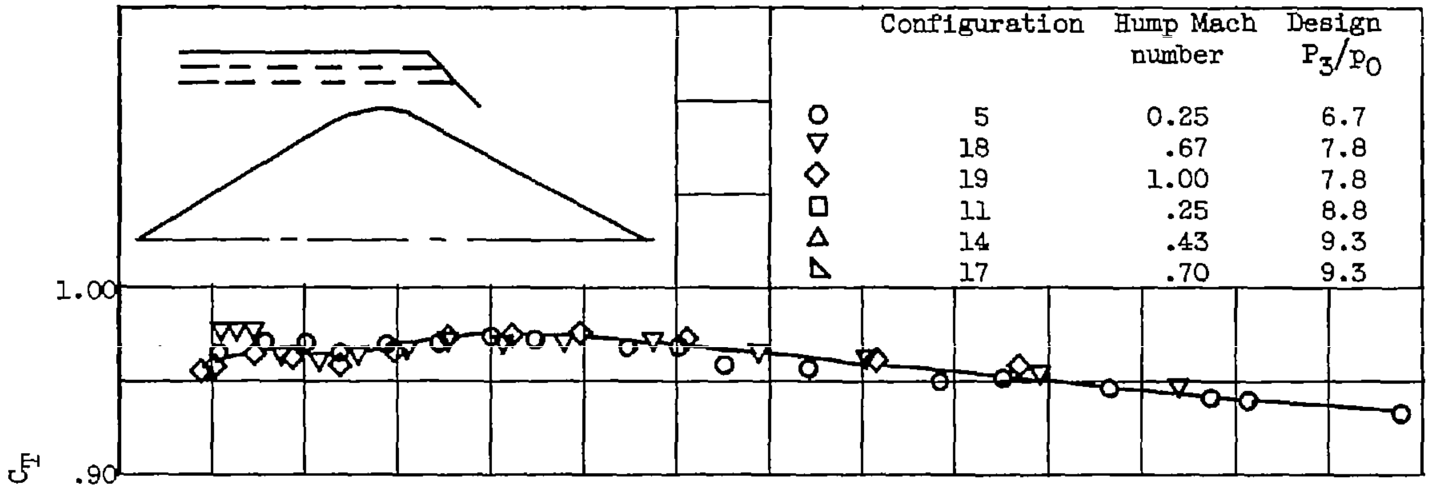
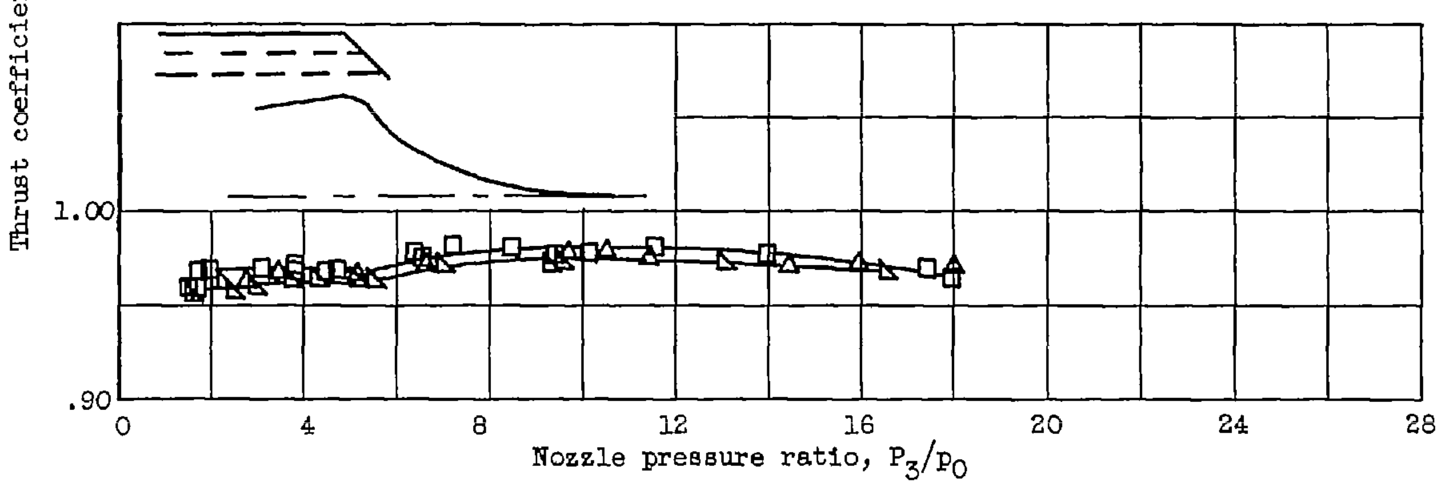


(a) Conical plug; design pressure ratio, approximately 7.



(b) Contoured plug; design pressure ratio, approximately 9.3.

Figure 10. - Effect of inlet Mach number.

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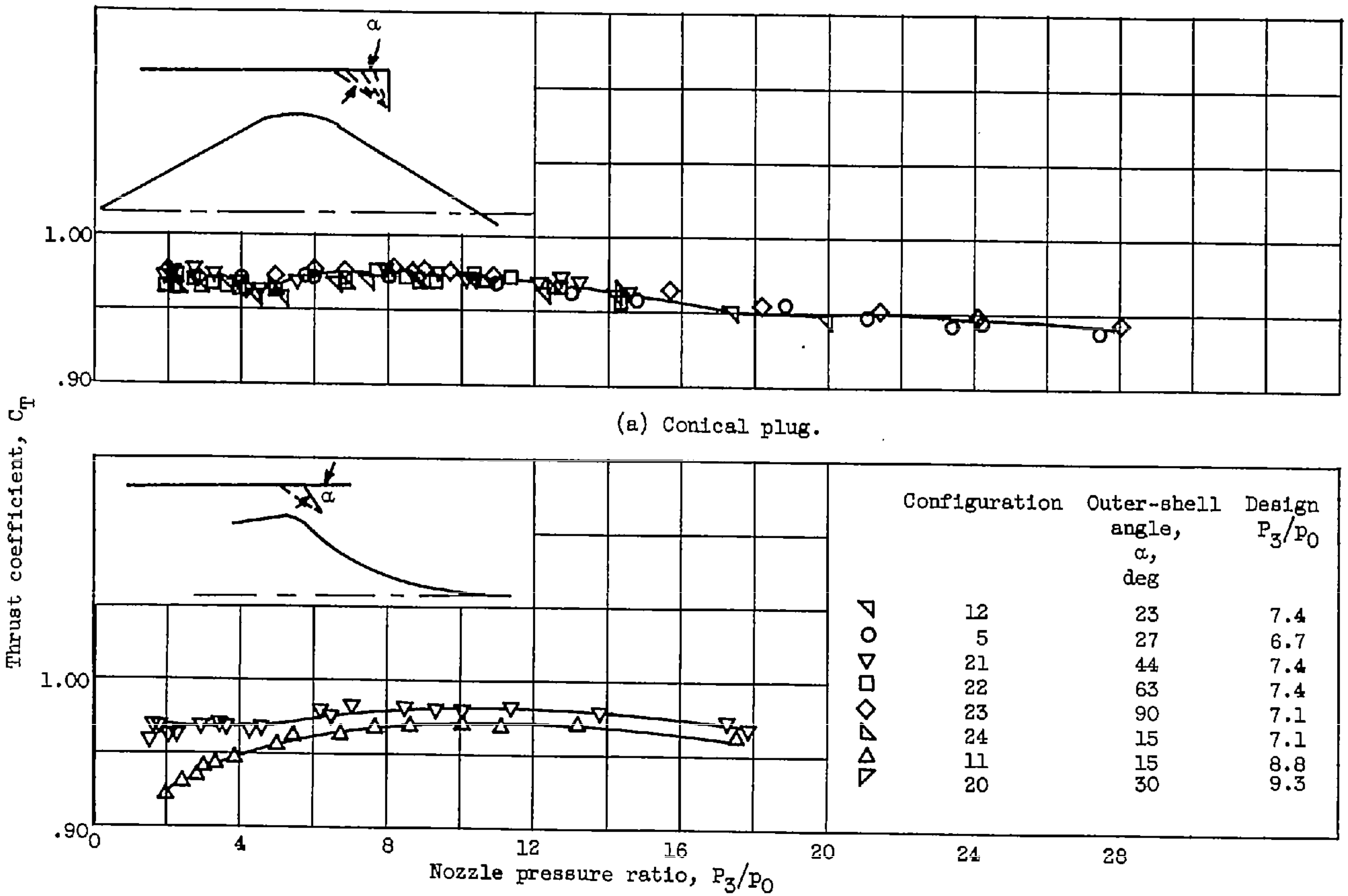

(a) Conical plug.

(b) Contoured plug.

Figure 11. - Effect of outer-shell lip angle.

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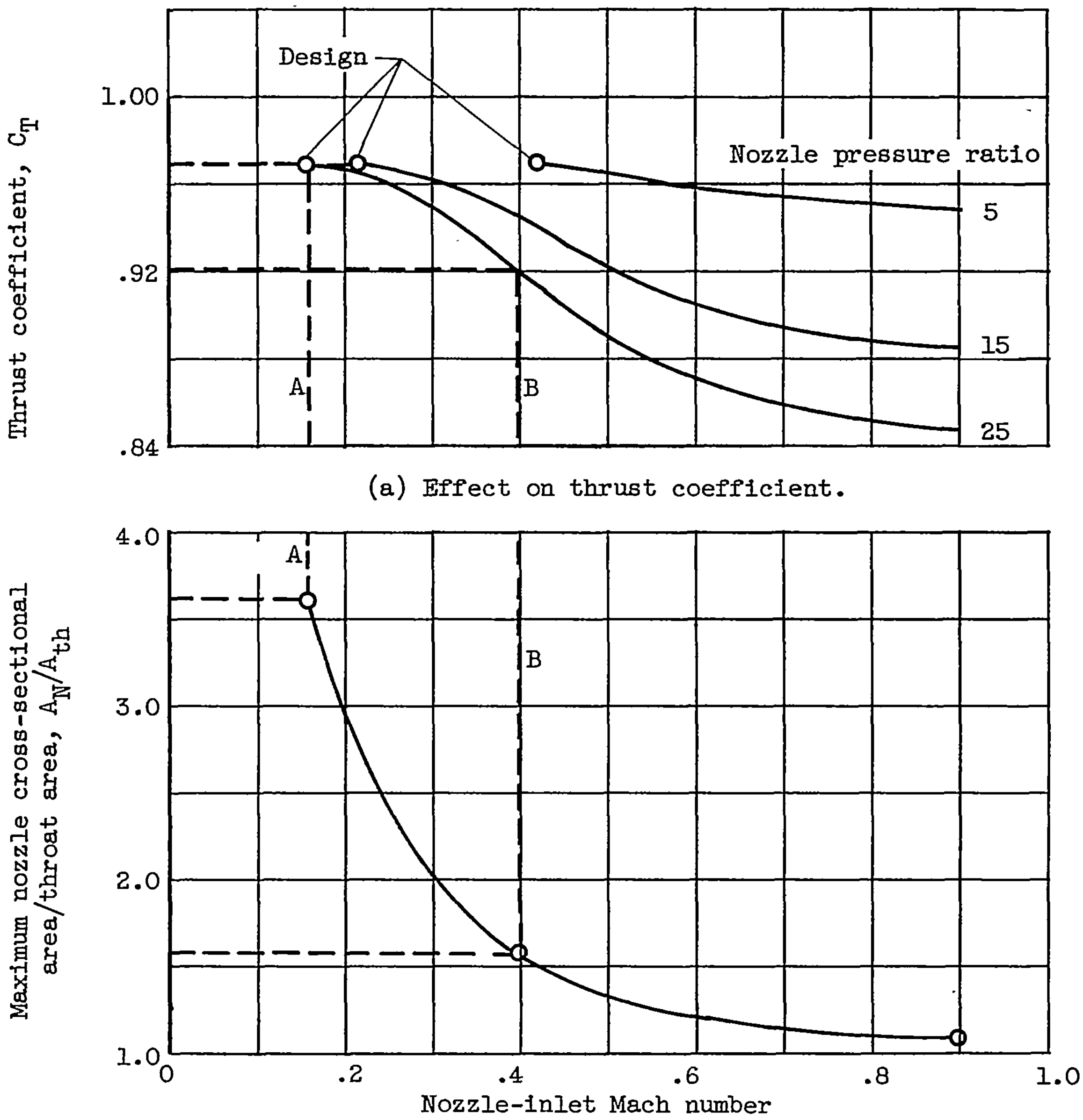

(a) Effect on thrust coefficient.

(b) Effect on nozzle size.

Figure 12. - Effect of inlet Mach number on conical-plug nozzle thrust coefficient and size.

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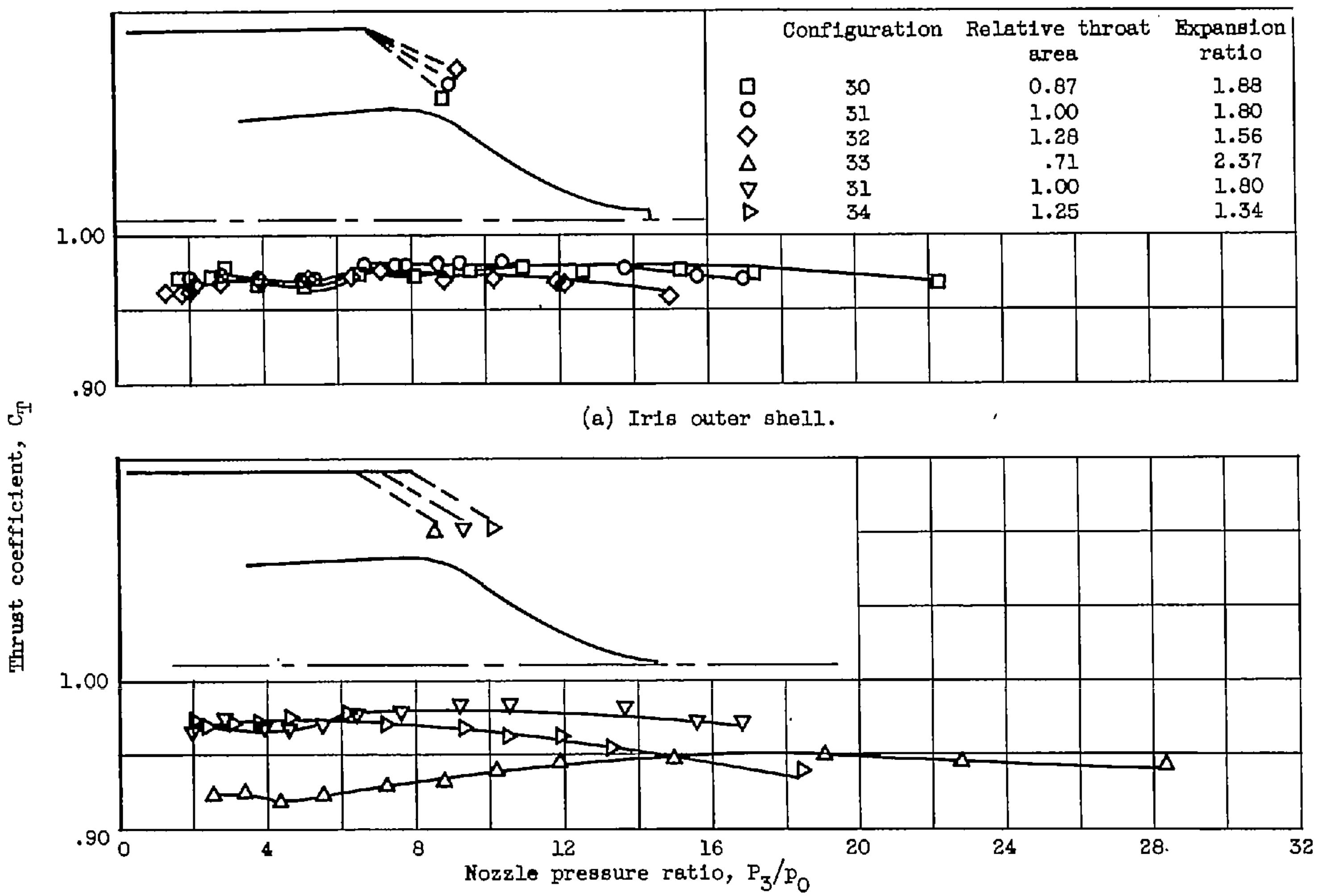

(a) Iris outer shell.

(b) Translatable outer shell.

Figure 13. - Effect of varying throat area of contoured-plug nozzle with simulated iris and translatable outer shells.

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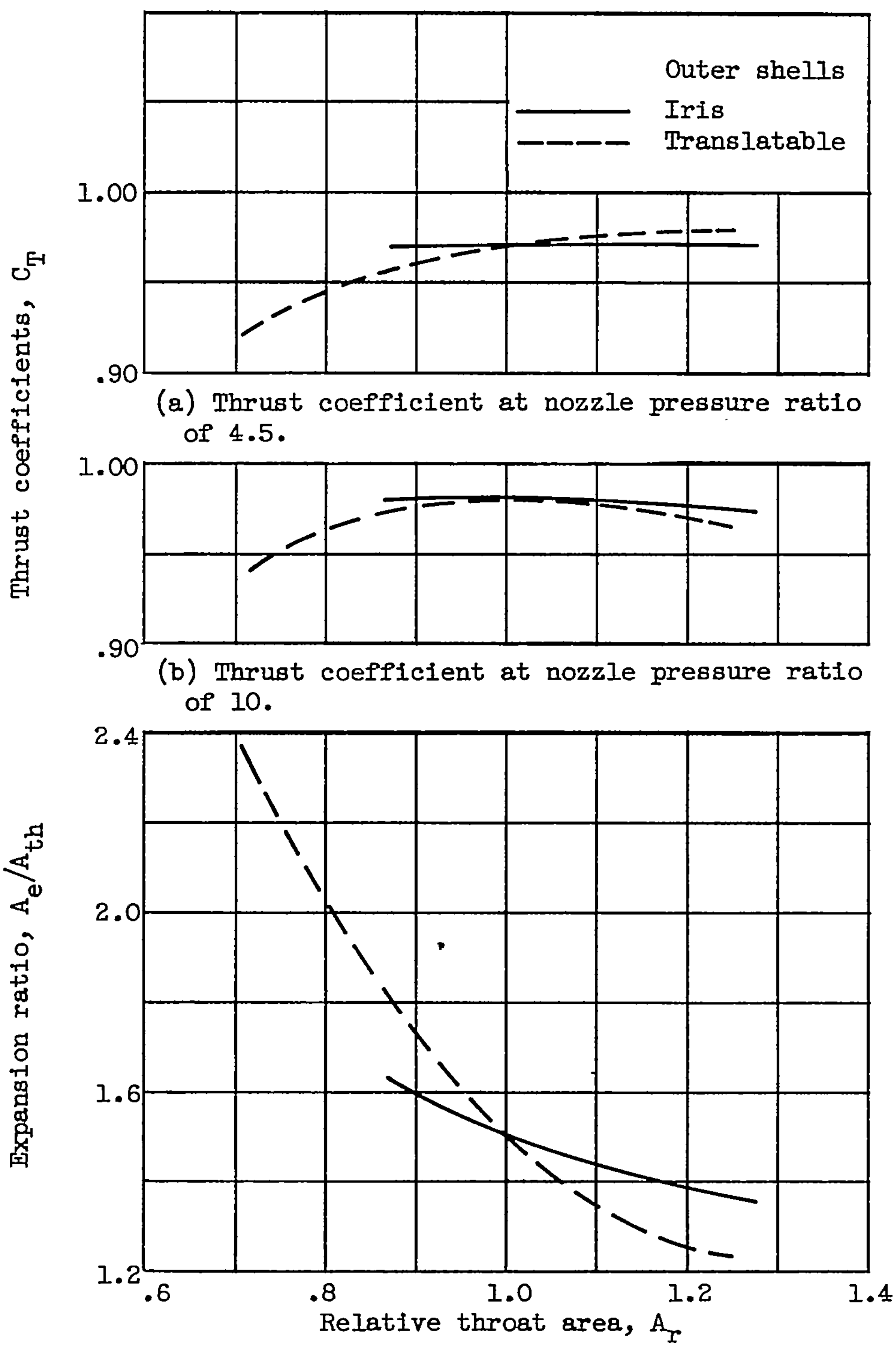

(a) Thrust coefficient at nozzle pressure ratio of 4.5.

(b) Thrust coefficient at nozzle pressure ratio of 10.

(c) Expansion ratio.

Figure 14. - Effect of throat-area variation on thrust coefficients and expansion ratio of contoured-plug nozzle.

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